UCRL-CONF-200553

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

DIII-D Experiments and Modeling of Core Confinement in Quiescent Double Barrier Plasmas

T. A. Casper, K. H. Burrell, E. J. Doyle, P. Gohil, C. M. Greenfield, R. J. Groebner, J. Jayakumar, C. J. Lasnier, A. W. Leonard, G. R. McKee, T. H. Osborne, T. L. Rhodes, P. Snyder, W. P. West, L. Zeng

October 24, 2003

9th IAEA Technical Meeting on H-Mode Physics and Transport Barriers
San Diego, CA, United States
September 24, 2003 through September 26, 2003

Disclaimer

DIII–D Experiments and Modeling of Core Confinement in Quiescent Double Barrier Plasmas

T.A. Casper,[1] K.H. Burrell,[2] E.J. Doyle,[3] P. Gohil,[2] C.M. Greenfield,[2] R.J. Groebner,[2] J. Jayakumar,[1] C.J. Lasnier,[1] A.W. Leonard,[2] G.R. McKee,[4] T.H. Osborne,[2] T. L. Rhodes,[3] P. Snyder,[2] W.P. West,[2] L. Zeng[3]

[1]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551 USA

[2]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA

[3]University of California, Los Angeles, Box 951597, Los Angeles, California 20742 USA

[4]University of Wisconsin, Madison, Wisconsin USA

Abstract. We continue to explore Quiescent Double Barrier (QDB) operation on DIII–D to address issues of critical importance to internal transport barrier (ITB) plasmas. QDB plasmas exhibit both a core transport barrier and a quiescent, H-mode edge barrier. Both experiments and modeling of these plasmas are leading to an increased understanding of this regime and it's potential advantages for advanced-tokamak (AT) burning-plasma operation. These near steady plasma conditions have been maintained on DIII–D for up to 4s, times greater than $35\tau_E$, and exhibit high performance with $\beta_N > 2.5$ and neutron production rates $S_n \sim 1x10^{16} s^{-1}$. Recent experiments have been directed at exploring both the current profile modification effects of electron cyclotron current drive (ECCD) and electron cyclotron (ECH) heating-induced changes in temperature, density and impurity profiles. We use model-based analysis to determine the effects of both heating and current drive on the q-profile in these QDB plasmas. Experiments based on predictive modeling achieved a significant modification to the q-profile evolution [1] resulting from the non-inductive current drive effects due to direct ECCD and changes in the bootstrap and neutral beam current drive components. We observe that the injection of EC power inside the barrier region changes the density peaking from $n_e/\langle n_e \rangle = 2.1$ to 1.5 accompanied by a significant reduction in the core carbon and high-Z impurities, nickel and copper.

High confinement mode (H-mode) operation is a leading scenario for burning plasma devices [2,3] due to its inherently high energy-confinement characteristics. The quiescent H-mode (QH-mode [4,5]) potentially offers these same advantages with the additional attraction of more steady edge conditions where the highly transient power loads due to edge localized mode (ELM) activity is replaced by the steadier power and particle losses associated with an edge harmonic oscillation (EHO)[4-6]. With the addition of an internal transport barrier (ITB), the capability is introduced for independent control of both the edge conditions and the core confinement region giving possible control of fusion power production in this advanced-tokamak (AT) configuration. The QDB [1, 4-9] conditions explored in DIII-D experiments exhibit these characteristics and have resulted in steady plasma conditions for several energy confinement times. Experiments were aimed at using these moderately high β, steady plasma conditions to explore the possibility for current profile control using electron-cyclotron heating (ECH) and current drive (ECCD).

These experiments, motivated by transport modeling to explore the effects of ECH and ECCD, were consistent with the modeling predictions [1,8,9] and provided an initial demonstration of the effects of current profile control in ITB plasmas in the DIII–D tokamak. As a result of direct ECCD, we observed significant changes in the q-profile both near the EC resonance location and at the magnetic axis due to inductive effects [1]. In addition to the current profile modification predicted, we also observed a reduction in the density profile peaking and an associated beneficial reduction in the total impurity concentration. These changes in density profiles resulted in secondary changes in the current profile both through modification of the neutral-beam-driven current (NBCD) and self-consistent changes in the bootstrap current, Fig. 1. In these counter-NBCD discharges, we observe a narrowing of the neutral-beam current profile resulting from a change in neutral-beam deposition due to changes in the electron temperature profile from heating and the density profile from changes in transport. We observed offsetting changes in the bootstrap current that was expected to increase with heating but was ultimately reduced by large changes in the local density gradient as the profile peaking is reduced. These profile-induced changes in current drive complicate the evolution of the q profile and its subsequent control but also afford the opportunity for simultaneous control of q, pressure and impurities.

In more recent experiments on DIII–D we continue to explore the effects of EC-power injection inside the ITB on the density, temperature and pressure profiles. In Fig. 2, we show the typically observed effect of EC-power injection inside the core barrier. Both the electron and ion thermal diffusivities increase with to the injection of EC power [9]. While the electron temperature increases due to the intense ECH, there is a reduction in the ion temperature with a slowing of the toroidal rotation and a drop in stored energy. Using a scan of the EC antenna launch conditions, we systematically explored the conditions for profile modification. As long as the power is injected inside the barrier with a peaked deposition profile (e.g., deposition localized to $\Delta\rho \sim 0.1$), the change in transport does not depend on the radial location of the resonance. Since the electron heating is dependent on the resonance location, we have independent control of the electron temperature (T_e) profile with respect to modifications of the density (n_e) and ion temperature (T_i) profiles. The current drive modification is, however, dependent on both the ECCD direction, e.g., co-, counter- and radial (no current drive) and on the radial deposition location. This provides for separate control of the magnetic shear profile with respect to the density profile changes. Since the T_e-profile is dependent on the radial location, it will be affected by antenna aiming to control the q-profile. This may be modified by separately aiming different launchers to optimize current drive versus electron heating. The magnitude of the change in transport as evidenced by the change in profiles is dependent on the amount of power injected and thus provides some control over the profile modification effects. Similarly, by broadening the EC-deposition profile, we have additional potential control of the shear and electron temperature profiles. In discharges with a broad deposition profile, e.g., power deposited over $0.15 < \rho < 0.5$, we observed the stabilization of a core n=1 mode and a somewhat weaker effect on the kinetic profiles. We also observed that the minimum in the q-profile remained approximately constant over a 2 second duration but the cause for this is not yet understood.

In these experiments, we also explored the possibility of recovering losses in plasma parameters (drop in β_N, toroidal rotation and T_i) by increasing the neutral beam heating during the EC injection into the ITB region. We show in Fig. 3 that, with the application of an additional 2.5 MW of neutral-beam heating (one additional beam), we can restore plasma conditions to the pre-EC values. As we show in Fig. 3, we are able exceed the pre-EC parameters with an additional ~5 MW of neutral-beam power (2 neutral beams). The additional heating pushes T_e, T_i, β_N and neutron rate above their pre-EC values while the line-average density returns to its initial value of $2.2 \times 10^{19} m^{-3}$. This recovery is achieved without a rise in the core impurities that remain at the EC-depressed levels, Fig. 3, and significantly below the no-EC discharge condition as shown in Figure 2. This indicates that we can control the impurity accumulation inside the barrier regions while increasing the stored energy. We also observe that the additional neutral-beam power has had the beneficial effect of raising q_0 well above 1.5 for the duration of the neutral beam and EC heating. This rise in q_0 is primarily due to the added neutral beam current drive that is peaked near the axis as indicated in Fig. 1. Since this is a counter-NBI shot, the increased NBCD reduces the total current drive near the magnetic axis thus allowing q_0 to rise. Finally, we note that these QDB discharges are quite robust to large modifications in the injected power with no loss in the QH-mode character even with a 50% increase in the neutral beam heating and the addition of 3MW of EC power. The plasma remains in the steady QDB state without returning to ELMing H-mode conditions.

In summary, by injecting in excess of 2MW of EC power with antennas aimed for ECCD, we were able to significantly modify the local minimum value of q and change the magnetic shear in the vicinity of the EC resonance and inside the resonance to the magnetic axis. By using co-, counter- or radial launch, we can modify the local magnetic shear profile inside the barrier region. In the case of broad current drive deposition we observed stabilization of an n=1 core mode. Injection of EC power inside the ITB heated the electrons as expected but also significantly altered the density profiles for electrons and impurities, changing the density peaking factor $n_e/\langle n_e \rangle$ from 2.1 to 1.5. This change in density resulted in modification to both the local bootstrap and neutral beam current drive components that, in turn, also modified the local q profile. This synergistic modification of the current profile will complicate development of q-profile control capabilities for these ITB discharges. However, in addition to current profile control, we have demonstrated the possibility for independently changing the density, temperature, pressure, impurity concentration and the magnetic shear profile as required for control of the barrier and possibly of β-limits as well. With additional neutral beam injection, we have indicated the ability to recover and exceed the pre-EC peak values of T_e, T_i, n_e, and β_N while raising q_{min} without increased accumulation of impurities in the core. With the additional heating, the impurities remain at the lower level achieved with the EC-modified transport. We are currently analyzing the details of the current profile modification that changes the magnetic shear and investigating the source of the strongly modified ion, electron and particle confinement due to EC-injection inside the ITB.

Acknowledgments

Work supported by U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, W-7405-ENG-48 (UC LLNL) and Grant Nos. DE-FG03-96ER54373 and DE-FGO3-01ER-54615.

References

[1] Casper, T. A., *et al*, Proc. 30th EPS Conference on Controlled Fusion and Plasma Physics, St.Petersburg, Russia, July 7-12, 2003.

[2] ITER Physics Basis Document, Nucl. Fusion **39**, 2137 (1999)

[3] Taylor, T.S., Plasma Phys. Controlled Fusion **39**, B47 (1997)

[4] Burrell, K.H. *et al.*, Phys of Plasmas **82**,153 (2001)

[5] Doyle, E.J. *et al.*, Plasma Phys and Control. Fusion **43**, A95 (2001)

[6] Greenfield C.M. *et al.*, Phys Rev Lett 20, 4544 (2001)

[7] Greenfield, C.M. *et al.*, Plasma Phys and Control. Fusion **44**, A123 (2002)

[8] Casper, T. A., *et al*, Proc. 29th EPS Conference on Controlled Fusion and Plasma Physics, Montreux, Switzerland, June 17-21, 2002.

[9] Doyle, E.J., *et al.,* 19th IAEA Fusion Energy Conference, EX/C3-2, Lyon, France, October 14-19, 2002.

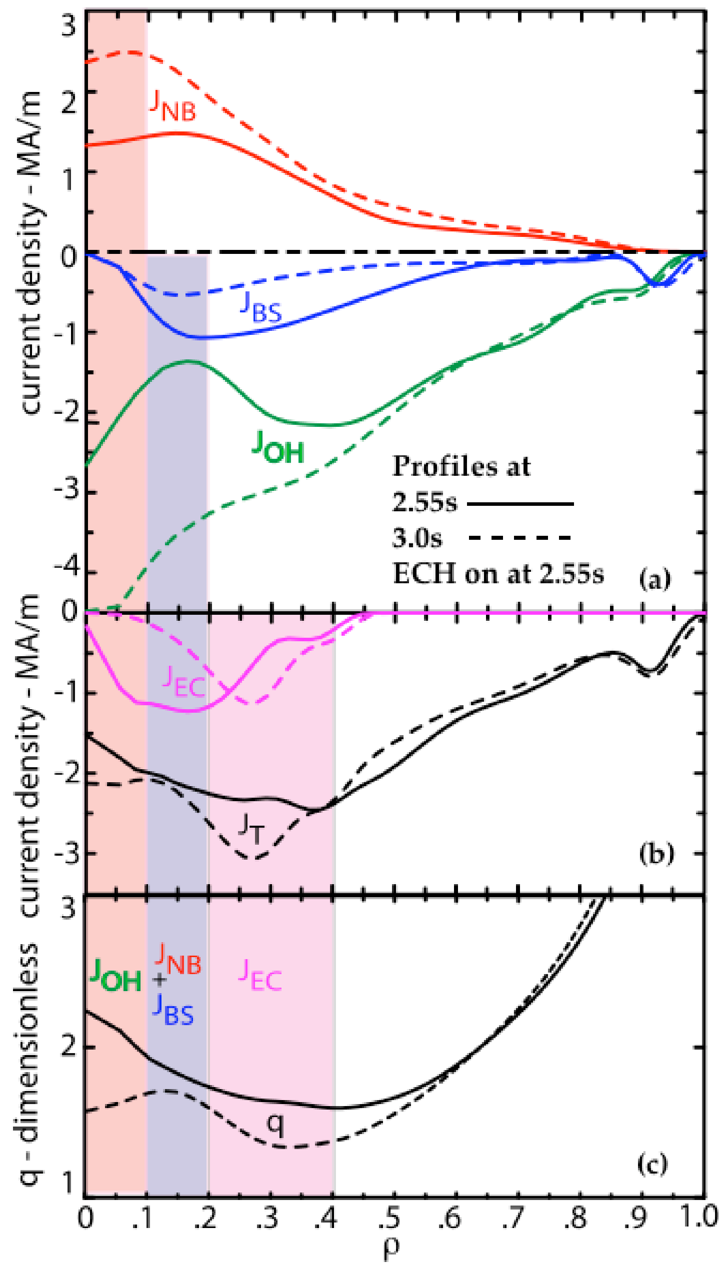

Fig. 1. Current and q-profile response to 2MW of EC power injected inside the ITB for DIII-D shot 110874. For waves launched in the co-ECCD direction at ⊔=0.25, the ECCD pushes q_{min} down while changes in the bootstrap and neutral beam currents enhance changes in magnetic shear.

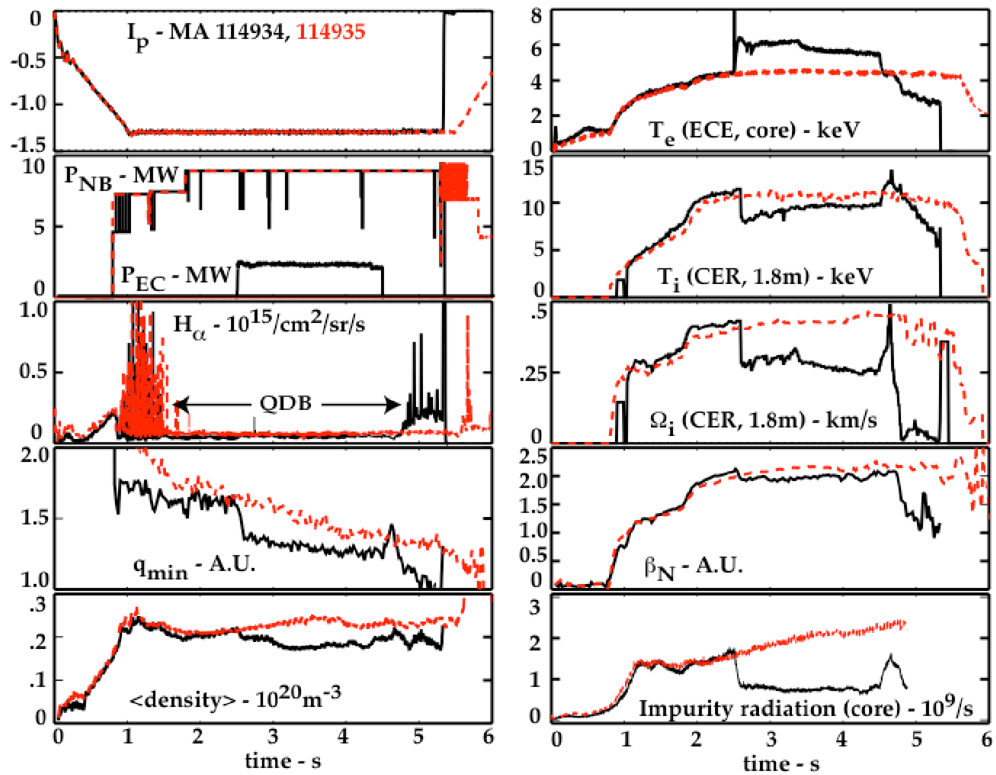

Fig. 2. Comparison of QDB plasma conditions for a no-ECCD reference shot, 114935, and shot 114935 with 2MW EC power with co-ECCD aiming at ⊔=0.25. Strong modification in the q_{min} along with changes in density, temperature and impurities are observed.

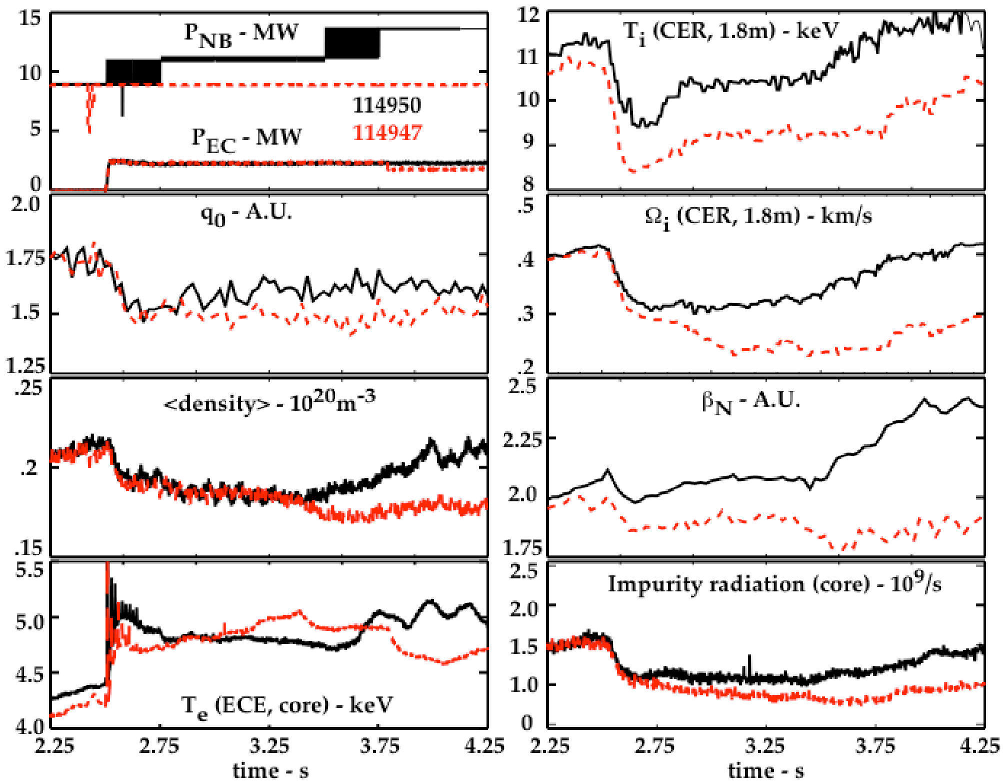

Fig. 3. Figure 3. Increasing the neutral beam power in shot 114950 recovers losses in density, temperature and neutron rate due to EC-power injection inside the barrier, shot 114947. Final values exceed the no-EC shot conditions shown in Figure 2 shot 114935 without increasing the core Z_{eff} while forcing q_0 above 1.5.